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M. Streicher

Manager, Advanced Systems Requirements, Systems Division, General Precision Aerospace

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M. Streicher
Manager, Advanced Systems Requirements
Systems Division
General Precision Aerospace
Wayne, New Jersey

Summary

This paper presents an examination of the guidance and navigation requirements for NASA's "MOLAB" vehicle (Mobile Lunar Lab.). The functions and capabilities necessary to guide and navigate a roving vehicle over the area of the lunar surface for exploration and experimental investigations are considered. A mission profile is afforded -- providing a general outline of environmental, navigation and guidance, and survey requirements.

The fact that the moon will eventually be explored by man is a foregone conclusion. Aside from the central fact that it exists and can be reached, which in the context of the entire history of the human race implies that it will someday be explored, there are other, more practical and compelling reasons. The moon should supply information on comparative planetology and the evolution of the solar system; it has potential as a way station enroute to other space destinations; it may prove to be a source of valuable minerals and raw materials. When the moon exploration will take place is more of an open question.

The idea of exploring the moon is, of course, not new. Earthbound explorations have been in progress for several centuries via the media of the telescope, the camera, and, more recently, radar. The last few years, however, have witnessed the first successful attempts at viewing the moon close-up. Ranger VII provided photographs of the lunar surface with detail which was, until then, unobtainable. The next step, Surveyor, will permit sampling the surface of the moon. Other lunar exploration programs now in the preparatory stage include the lunar orbiter system, which is scheduled for its first flight in 1966. But all of these programs have restrictions of one sort or another. Either they do not provide a means of sampling the surface or they provide limited coverage. What will ultimately be required is an integrated overall program to obtain information on the total moon. Such a program should include:

1. Orbital surveys, such as the lunar orbiter, which utilize photography and other parts of the electromagnetic spectrum as well as geophysical methods (e.g., gravity anomaly detection).

2. Fixed site exploration, such as that which would be carried out by the Surveyor, and later by manned permanent or semi-permanent bases. These explorations would be in considerable detail and over fairly long periods of time, permitting the addition of a temporal factor to the experimentation.

3. Surface exploration, by means of surface traverses during which geological, geochemical, and geophysical investigations would be made. It is with these surface explorations that this paper is primarily concerned. Most of the lunar explorations now in preparation are directed at Apollo landing site certification. The first mobile lunar surface exploration system

not restricted to Apollo landing site studies is known as Molab, an acronym for Mobile Lunar Laboratory.

Scientists have identified twenty uniquely different types of major terrain features on the lunar surface.[1] They add to this two general categories; stratigraphic contacts and special features (Alphonsus, Aristarchus, etc.) The Kepler area contains fourteen of the twenty uniquely different types of features plus several stratigraphic contacts. It has been estimated by others that exploration of three such areas would yield information on 97% of the surface feature types.

Molab is part of ALSS (Apollo Logistic Support System). This concept requires two Apollo launches - one to deliver the Molab including support equipment and supplies, the other to transport two astronauts to the general site of the previously landed Molab. In the Cargo Apollo (unmanned), the LEM would be modified for unmanned lunar landing and the ascent stage would be replaced by Molab. This version of the LEM is commonly called the LEM truck, and the Molab it could place on the moon will probably weigh 5000-6000 lbs. Extensive lunar exploration from a fixed site would be made possible by utilization of the LESA (Lunar Exploration System for Apollo) concept. A Saturn launch would place 25,000 lbs of material on the lunar surface using a direct flight technique. The payload would include a Molab type vehicle and a large shelter-laboratory. A payload of this type could support a 90 day exploration mission by three astronauts, including 1500 miles of exploratory traverses.

Molab Requirements

The remainder of the paper will concern itself with the problem of navigation of the Molab on the surface of the moon. The Molab requirements which effect its navigation guidance and control are:

1. capability of automatic check-out and operation from the earth;

2. capability of maintaining a dormant or standby mode on the moon for six months;

3. capability of operation during the lunar day or night for a period of 14 days and;

4. capability of traversing a distance of 250 miles (all within a 50 mile radius of the starting point) at speeds up to 10 mph.

A typical mission profile would include: (1) unmanned landing of the LEM truck, (2) initial remote checkout from earth, (3) unloading, (4) final checkout, (5) storage for up to six months with intermediate checkouts from earth, (6) final checkout prior to launch of a manned Apollo from earth, (7) launch of a manned Apollo, (8) landing of manned LEM in the vicinity of the Molab, (9) remote call-up of the Molab to the manned LEM, (10) manned exploration of the lunar surface over a 14 day period, and (11) return to the LEM and then back to earth.

Navigation is required for two reasons: (1) to assure the ability to locate the LEM for the return to earth and (2) to be able to locate any point in the traverse for future reference.

Navigation Modes

In accomplishing its mission the MOLAB will operate in several different navigation modes. These modes are:

1. The remote control mode, which requires that the navigation equipment be capable of self checking, automatically bringing itself to a condition of readiness and finally negotiating

the lunar surface under control of a remote control station so as to arrive at a point selected by the remote control station;

2. The normal traverse mode, which is used to traverse the lunar surface with the complement of two astronauts aboard. This mode will most likely require negotiating a predetermined traverse (fig. 1), proceeding from point to point with the ability to deviate when faced with obstructions and return to the nominal traverse. Vehicle position in this mode must be recorded for future use in reducing data collected and also in the eventuality that it becomes necessary or desirable to retrace the traverse and in this manner return to the LEM.

3. The accurate position fix mode, which is used when it is required to locate a point with the best possible accuracy and while the vehicle is stationary. This mode is utilized to obtain initial conditions and correct any accumulated errors in the navigation system.

4. The survey mode, which requires making accurate angle and range measurements for the purpose of synthesizing selinological maps. This mode should be able to determine relative elevation (altitude) among the various points surveyed.

Completely Self-Contained System

Several methods of self-contained navigation come immediately to mind. The first, and perhaps most versatile, is a stellar-inertial system. Such a system is capable of supplying continuous position data with automatic readout, thereby greatly reducing the work load on the astronauts. It also supplies initial position. Time dependent errors can be reduced or removed at any time by obtaining a star fix. In addition, the mission is such that the accumulated velocity error can be set to zero by merely coming to a standstill and setting the velocity output to zero. Such a system would use the local vertical as a reference for taking star direction measurements and so would be sensitive to gravity anomalies. At present the values and locations of such anomalies are unknown; indeed they would be determined by lunar exploration. The existence of gravity anomalies would introduce surface location errors of approximately 30 ft per arc second of deviation. Some people have suggested using 1 arc minute as a maximum gravity anomaly. A complete stellar-inertial system including cover and mounting provisions would weigh less than 50 pounds, take up one cubic foot, and require 250 watts of power. Such a system would be capable of defining the local vertical to 10 arc seconds, measure line of sight to stars within 5 arc seconds, locate itself in the stellar mode to within 330 ft, and maintain an accuracy in the inertial mode of better than 1000 ft/hr.

Such an instrumentation would require for the remote control mode the addition of two (stereo pair) TV cameras designed to observe the lunar surface. These cameras plus the attitude reference supplied by the stellar-inertial system would allow remote operation and call-up. If we add to this a magnetic tape storage system, we have extended the system capability to include the survey or mapping mode. Thus all the required modes of navigation are possible with such an instrumentation. An instrumentation of this type has the following advantages:

1. completely self-contained;

2. continuous information available;

3. minimum navigation work load on astronauts;

4. not limited by line of sight (either from point to point on the moon or from the moon to the earth) and therefore useful any place on the lunar surface;

5. capable of providing its own initial conditions;

6. capable of providing detail pictures for mapping purposes.

Its main disadvantages are:

1. complex equipment

2. lack of knowledge of gravity anomalies.

In an attempt to remove gravity anomaly uncertainties a brief examination of references (fig. 2) other than local vertical was made. Measuring star directions (two required) against the local vertical gives rise to position errors of approximately 50 ft per arc sec of error in the measurement or in the local vertical. However,

1. Using as a reference the line from the Molab's position on the moon to the center of the earth gives rise to an error which is dependent upon the vehicle's lunar latitude. If the readings are taken from a point on the lunar equator, an error in defining this reference in measuring the star angle yields an error of one mile per arc second. At a lunar latitude of 45° this error becomes 13 miles per arc second.

2. Using a line from the observer's lunar surface position to a low orbit moon satellite yields an error coefficient about twice that for the local vertical case.

Cases 1 and 2 are even worse than they appear, since in addition to having larger error coefficients, both of them have inherently larger measurement errors in defining the reference. The error in the earth line definition arises because the earth is not a point source and the error in the satellite line is due to limited accuracy in the knowledge of its ephemeris.

DSIF Dependent System

At the other end of the spectrum is an instrumentation which relies to a great extent on earth-based equipment for navigation. This instrumentation relies upon the DSIF (Deep Space Instrumentation Facility) to define the position of the Molab on the moon's surface. It requires that the Molab be within the line of sight (fig. 3) of the DSIF for a position fix and further depends upon maintenance of a communication link to relay position information thus obtained to the crew of the Molab.

The equipment required on board the Molab for this instrumentation is simpler than that for the previous instrumentation. A beacon transponder may be desirable for DSIF signal enchancement. A communication link will be needed but is required for other purposes and so cannot be properly charged to the navigation system. Read-out equipment and displays can be considered as being similar to that used with the stellar-inertial instrumentation and these will be ignored here as they were there. The position location capabilities of this system are on the order of 100 meters. Complete reliance on the DSIF for navigation has the advantage that errors are not time dependent and the instrumentation is simple.

Let us examine how such an instrumentation satisfies the various modes of operation. It is conceivable that for remote call-up the DSIF can locate both the manned LEM and the MOLAB and then guide the MOLAB to the LEM. However, it is possible that it may be undesirable to cross the intervening terrain directly and that the DSIF would be incapable of detecting this and providing proper steering signals. It thus becomes desirable to include the TV stereo pair as in the stellar-inertial instrumentation and an attitude reference.

We therefore find ourselves including a star tracker for heading reference and a simple platform, which has bubble levels in place of the two accelerometers but is otherwise the same as the platform for the stellar-inertial system.

Again, the addition of magnetic tape storage for video information allows a survey mode of operation and we have a system capable of performing in all the required navigation modes. But what really is the difference in complexity between this which we will call "DSIF Dependent Instrumentation" and the "Stellar Inertial Instrumentation?" The difference is two accelerometers and some computer capability. It would appear that the DSIF would make a cheap back up system but doesn't save much as a primary system over the stellar-inertial approach.

The disadvantages of such an instrumentation are:

1. It is not self-contained. (While this system is more reliable than the previous one its failure is more dangerous.)

2. The line of sight requirement restricts areas which can be explored.

3. Navigation information is not continuous and an additional navigational work load is imposed on the crew if they desire to interpolate between DSIF fixes.

5th Wheel System

Another candidate system uses a fifth wheel in conjunction with a heading and elevation (pitch) reference system. Such a system has been tested and has proved quite accurate on earth. The results of these tests are not included here due to security restrictions. Analysis and tests have been carried out over a period of five years, and considerable work has been performed in analyzing road noise and performance in snow. The fifth wheel concept can be implemented either by a wheel in contact with the ground or by counting drive shaft revolutions. The true fifth wheel can provide better slippage characteristics since it need not be a load bearing wheel. However, the moon environment may well negate this desirable characteristic. The drive shaft approach suffers from the fact that slippage in the load bearing wheel is reflected as errors in the "distance traveled" computation.

Lack of knowledge of the characteristics of the moon's surface makes the 5th wheel a risky type of instrumentation.[2] If it turns out that the fifth wheel is in fact usuable on the moon surface, then the addition of a fifth wheel (odometer) to the DSIF instrumentation allows for interpolation between DSIF fixes and provides the additional feature of allowing accurate measurements of altitude variations during the traverse. This feature is highly desirable.

The instrumentation required for the fifth wheel consists of the sensor (fifth wheel) itself, the heading reference, and the local vertical reference. Navigation using this approach would be accomplished by a simple dead-reckoning technique, with instantaneous "north," "east," and vertical velocities found by resolving the speed of the vehicle, supplied by the fifth wheel, about the elevation and azimuth angles as provided by the vertical and heading reference. Thus, a principal disadvantage to this scheme is that it requires, along with the primary fifth wheel sensor, secondary sensors which must provide a vertical reference and an azimuth reference -- basically, a platform. These secondary sensors amount to almost the same complexity as the complete reference for the stellar-inertial technique.

Laser Velocimeter

A hitherto unknown velocity sensing technique has been developed by GPL Division of General Precision, Inc. and has certain unique characteristics which make it applicable to surveying or navigation over the lunar surface. The output beam of a laser is directed downward at the surface and the light which is backscattered is received in a photomultiplier which has an appropriate reticle on its surface. The signal derived from the photomultiplier consists of a narrow band of frequencies whose center is directly proportional to the speed of the vehicle over the surface. This signal frequency may be integrated to provide a measure of the total distance traveled.

Briefly explained, the concept underlying this velocimeter uses the unique behavior of coherent light when it is reflected from a diffuse surface. The light is backscattered in discrete fine lobes (the re-radiation pattern lobes can be imagined to resemble the petals of a chrysanthemum flower) which remains stationary if there is no relative motion between the light source and the surface. However, as the laser is transported across the surface this multi-lobed pattern appears to move counter to the laser motion with equal speed. The receiver photomultiplier has an optical grating whose spacing is optimized so that as each lobe of the pattern crosses the bars of the grating the light falling on the phototube face is chopped at a frequency equal to the velocity of the lobe across the grating times the number of grating lines per unit distance.

The features of this velocimeter are its inherent accuracy and the fact that it does not contact the surface. As a land navigator, accuracies of 0.1% have been shown by actual tests to be feasible. Field tests of a system which consisted of a 0.5 mv Helium-neon laser, a photomultiplier, associated frequency measuring electronics, a gyro compass, navigation computer and map plotter have been made in a station wagon with excellent results as an automatic dead reckoning navigation system.

The largest and heaviest component in the current equipment is the helium-neon laser. Assuming that solid state lasers at the milliwatt level of output will be available by 1970, it is estimated that this sensor with the required electronics can weigh less than four pounds and require an input of less than 5 watts. This sensor can be used in a manner similar to the fifth wheel without its drawback of slippage and can also be used to supply velocity information for damping a Schuler tuned stellar-inertial system.

Piloting By Sighting on Landmarks

A reliable, proven navigation technique which must be considered here, is that of the use of known surface features for triangulation. No heading reference is required for navigation, but several serious disadvantages present themselves.

1. Accurate charts of the surface features to be used for navigation (probably mountains) must be available. On the side of the moon facing the earth, these are already available. On the "back" side, they may not be available for some time; indeed, the purpose of the Molab mission may be, in part, to generate data for such charts.

2. Features usable for navigation must be available within the line of sight. Behind lunar cliffs and other topological features, this may be a serious problem.

3. Continuous navigational data would not be available. Astronaut-performed fixes would be the source of navigation data. One solution to this problem might be to place

radiating beacons, which could be automatically tracked, at these features, but the logistics problem then becomes formidable. We must conclude, therefore, that this old technique of earth navigation would not appear to be directly applicable, at least to early Molab missions.

Selection of System

A comparison of these systems leads this writer to the selection of the stellar-inertial system with the laser velocimeter included for primary navigational data. It does not require an unobstructed line-of-sight to the earth; the platform portion appears to be a basic ingredient of any system chosen; and continuous navigation data is desired.

Alignment and calibration would be accomplished using the optical portion of the system. Position fixes for this purpose could be obtained by:

1. measuring the angles between two known stars and the local vertical;
2. measuring the angles between two stars and a circumlunar satellite;
3. measuring the angles between two stars and the line to the earth's center.

As mentioned earlier, the first technique leads to errors of 30 ft/arc-sec of error in measuring the star angles. The second technique, which has the shortcomings of requiring a circumlunar satellite with known ephemerides within the line-of-sight, leads to errors of about 60 ft/arc-sec in the angle measurement. The third technique, which requires that the earth be within the line-of-sight, yields errors of about 1 n.m./arc sec. The logical choice, from all viewpoints then, is the first, which is a natural technique for a stellar-inertial system.

A pair of TV cameras would be included for the remote control mode and with the addition of magnetic tape storage the survey mode is also included. DSIF information would be used as a back-up for the prime system.

Acknowledgements

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References

1. "Extended Lunar Exploration," by Major Thomas C. Evans, presented at the 10th Annual American Astronautical Society Meeting, May 4-7, 1964.

2. Bendix Report BSR 903, April 1964.

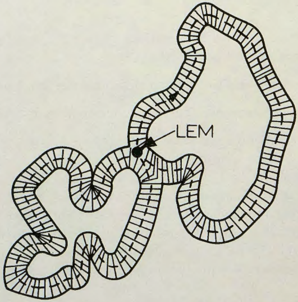

Figure 1 A figure 8 traverse is used to allow maximum coverage within a 50 mile radius. Such a traverse also provides a convenient abort opportunity halfway through the mission.

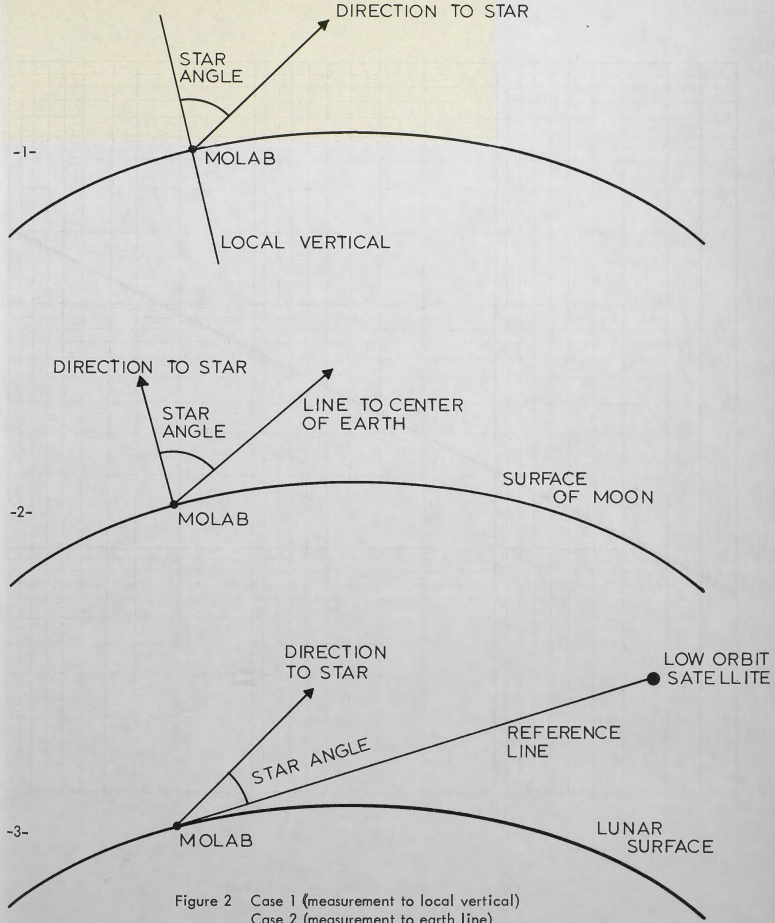

Figure 2 Case 1 (measurement to local vertical)
Case 2 (measurement to earth line)
Case 3 (measurement to satellite line)

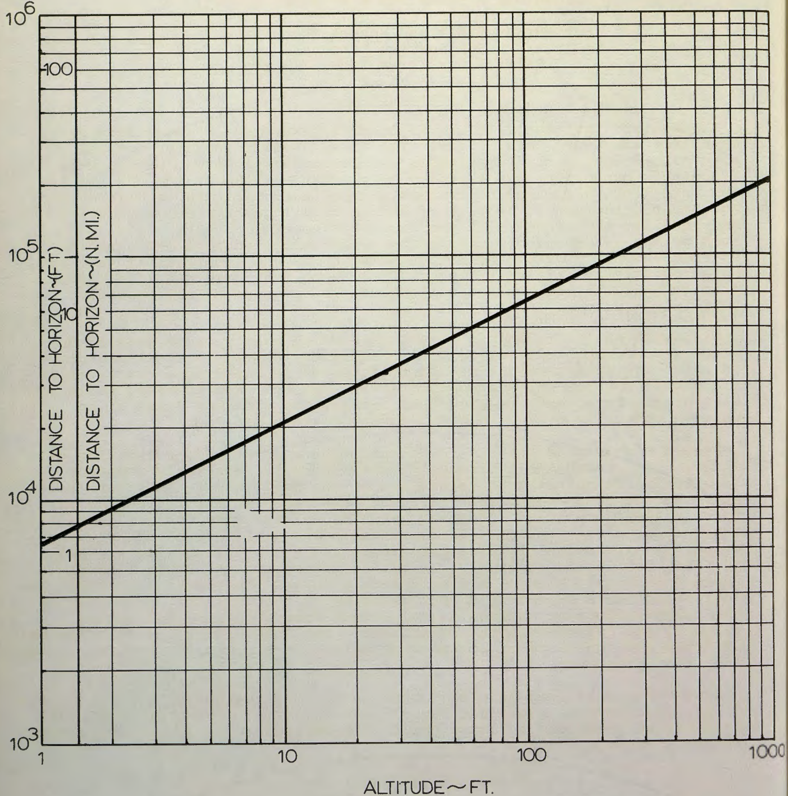

Figure 3 Distance to Horizon vs. Altitude